

ASTROPHYSICS OF PLANET FORMATION

Concise and self-contained, this textbook gives a graduate-level introduction to the physical processes that shape planetary systems, covering all stages of planet formation. Writing for readers with undergraduate backgrounds in physics, astronomy, and planetary science, Armitage begins with a description of the structure and evolution of protoplanetary disks, moves on to the formation of planetesimals, rocky, and giant planets, and concludes by describing the gravitational and gas dynamical evolution of planetary systems. He provides a self-contained account of the modern theory of planet formation and, for more advanced readers, carefully selected references to the research literature, noting areas where research is ongoing.

The second edition has been thoroughly revised to include observational results from NASA's *Kepler* mission, *ALMA* observations and the *JUNO* mission to Jupiter, new theoretical ideas including pebble accretion, and an up-to-date understanding in areas such as disk evolution and planet migration.

PHILIP J. ARMITAGE is a professor in the Department of Physics and Astronomy at Stony Brook University and he leads the planet formation group at New York's Center for Computational Astrophysics. He teaches classes on planet formation to advanced undergraduate and graduate students, and has lectured on the topic at summer schools worldwide.

Cambridge University Press
978-1-108-42050-1 — Astrophysics of Planet Formation
Philip J. Armitage
Frontmatter
[More Information](#)

ASTROPHYSICS OF PLANET FORMATION

SECOND EDITION

PHILIP J. ARMITAGE

*Stony Brook University and
Center for Computational Astrophysics*



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org

Information on this title: www.cambridge.org/9781108420501

DOI: 10.1017/9781108344227

© Philip J. Armitage 2009, 2020

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2009

Second edition 2020

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall
A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data

Names: Armitage, Philip J., 1971– author.

Title: Astrophysics of planet formation / Philip J. Armitage (Stony Brook University and Center for Computational Astrophysics).

Description: Second edition. | Cambridge : Cambridge University Press, 2020. | Includes bibliographical references and index.

Identifiers: LCCN 2019038227 (print) | LCCN 2019038228 (ebook) | ISBN 9781108420501 (hardback) | ISBN 9781108344227 (epub)

Subjects: LCSH: Planets—Origin. | Astrophysics.

Classification: LCC QB603.O74 A76 2020 (print) | LCC QB603.O74 (ebook) | DDC 5234—dc23

LC record available at <https://lccn.loc.gov/2019038227>

LC ebook record available at <https://lccn.loc.gov/2019038228>

ISBN 978-1-108-42050-1 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

	<i>page</i>
<i>Preface</i>	<i>xi</i>
1 Observations of Planetary Systems	1
1.1 Solar System Planets	2
1.2 The Minimum Mass Solar Nebula	4
1.3 Minor Bodies in the Solar System	6
1.4 Radioactive Dating of the Solar System	9
1.4.1 Lead–Lead Dating	12
1.4.2 Dating with Short-Lived Radionuclides	13
1.5 Ice Lines	14
1.6 Meteoritic and Solar System Samples	16
1.7 Exoplanet Detection Methods	18
1.7.1 Direct Imaging	19
1.7.2 Radial Velocity Searches	21
1.7.3 Astrometry	26
1.7.4 Transits	27
1.7.5 Gravitational Microlensing	32
1.8 Properties of Extrasolar Planets	34
1.8.1 Parameter Space of Detections	35
1.8.2 Orbital Properties	37
1.8.3 Mass–Radius Relation	40
1.8.4 Host Properties	42
1.9 Habitability	44
1.10 Further Reading	48
2 Protoplanetary Disk Structure	49
2.1 Disks in the Context of Star Formation	49
2.2 Observations of Protostellar Disks	51
2.2.1 Accretion Rates and Lifetimes	52
2.2.2 Inferences from the Dust Continuum	53
2.2.3 Molecular Line Observations	55

vi	<i>Contents</i>	
	2.2.4 Transition Disks	56
	2.2.5 Disk Large-Scale Structure	56
2.3	Vertical Structure	57
2.4	Radial Force Balance	59
2.5	Radial Temperature Profile of Passive Disks	60
	2.5.1 Razor-Thin Disks	61
	2.5.2 Flared Disks	63
	2.5.3 Radiative Equilibrium Disks	65
	2.5.4 The Chiang–Goldreich Model	68
	2.5.5 Spectral Energy Distributions	69
2.6	Opacity	71
2.7	The Condensation Sequence	73
2.8	Ionization State of Protoplanetary Disks	75
	2.8.1 Thermal Ionization	75
	2.8.2 Nonthermal Ionization	76
2.9	Disk Large-Scale Structure	80
	2.9.1 Zonal Flows	80
	2.9.2 Vortices	81
	2.9.3 Ice Lines	83
2.10	Further Reading	85
3	Protoplanetary Disk Evolution	86
	3.1 Observations of Disk Evolution	86
	3.2 Surface Density Evolution of a Thin Disk	88
	3.2.1 The Viscous Time Scale	90
	3.2.2 Solutions to the Disk Evolution Equation	91
	3.2.3 Temperature Profile of Accreting Disks	95
	3.3 Vertical Structure of Protoplanetary Disks	96
	3.3.1 The Central Temperature of Accreting Disks	97
	3.3.2 Shakura–Sunyaev α Prescription	98
	3.3.3 Vertically Averaged Solutions	100
	3.4 Hydrodynamic Angular Momentum Transport	102
	3.4.1 The Rayleigh Criterion	102
	3.4.2 Self-Gravity	103
	3.4.3 Vertical Shear Instability	106
	3.4.4 Vortices	107
	3.5 Magnetohydrodynamic Angular Momentum Transport	109
	3.5.1 Magnetorotational Instability	109
	3.6 Effects of Partial Ionization and Dead Zones	114
	3.6.1 Ohmic Dead Zones	114
	3.6.2 Non-ideal MHD Terms	117
	3.6.3 Non-ideal Induction Equation	118

Contents

vii

3.6.4	Density and Temperature Dependence of Non-ideal Terms	123
3.6.5	Application to Protoplanetary Disks	124
3.7	Disk Winds	127
3.7.1	Condition for Magnetic Wind Launching	128
3.7.2	Net Flux Evolution	132
3.8	Disk Dispersal	133
3.8.1	Photoevaporation	134
3.8.2	Viscous Evolution with Photoevaporation	135
3.9	Magnetospheric Accretion	137
3.10	Further Reading	140
4	Planetesimal Formation	141
4.1	Aerodynamic Drag on Solid Particles	142
4.1.1	Epstein Drag	142
4.1.2	Stokes Drag	143
4.2	Dust Settling	144
4.2.1	Single Particle Settling with Coagulation	145
4.2.2	Settling in the Presence of Turbulence	147
4.3	Radial Drift of Solid Particles	149
4.3.1	Radial Drift with Coagulation	153
4.3.2	Particle Concentration at Pressure Maxima	154
4.3.3	Particle Pile-up	155
4.3.4	Turbulent Radial Diffusion	156
4.4	Diffusion of Large Particles	158
4.5	Particle Growth via Coagulation	160
4.5.1	Collision Rates and Velocities	160
4.5.2	Collision Outcomes	162
4.5.3	Coagulation Equation	163
4.5.4	Fragmentation-Limited Growth	165
4.6	Gravitational Collapse of Planetesimals	166
4.6.1	Gravitational Stability of a Particle Layer	167
4.6.2	Application to Planetesimal Formation	172
4.6.3	Self-Excited Turbulence	173
4.7	Streaming Instability	176
4.7.1	Linear Streaming Instability	176
4.7.2	Streaming Model for Gravitational Collapse	177
4.8	Pathways to Planetesimal Formation	178
4.9	Further Reading	180
5	Terrestrial Planet Formation	181
5.1	Physics of Collisions	181
5.1.1	Gravitational Focusing	182

viii	<i>Contents</i>	
	5.1.2 Shear versus Dispersion Dominated Encounters	183
	5.1.3 Accretion versus Disruption	186
5.2	Statistical Models of Planetary Growth	190
	5.2.1 Approximate Treatment	191
	5.2.2 Shear and Dispersion Dominated Limits	193
	5.2.3 Isolation Mass	197
5.3	Velocity Dispersion	198
	5.3.1 Viscous Stirring	199
	5.3.2 Dynamical Friction	202
	5.3.3 Gas Drag	203
	5.3.4 Inelastic Collisions	204
5.4	Regimes of Planetesimal-Driven Growth	205
5.5	Coagulation Equation	207
5.6	Pebble Accretion	210
	5.6.1 Encounter Regimes	212
	5.6.2 Pebble Accretion Conditions	213
	5.6.3 Pebble Accretion Rates	216
	5.6.4 Relative Importance of Pebble Accretion	216
5.7	Final Assembly	217
5.8	Further Reading	219
6	Giant Planet Formation	220
6.1	Core Accretion	221
	6.1.1 Core/Envelope Structure	226
	6.1.2 Critical Core Mass	230
	6.1.3 Growth of Giant Planets	233
6.2	Constraints on the Interior Structure of Giant Planets	237
	6.2.1 Interior Structure from Gravity Field Measurements	238
	6.2.2 Internal Structure of Jupiter	239
6.3	Disk Instability	240
	6.3.1 Outcome of Gravitational Instability	241
	6.3.2 Cooling-Driven Fragmentation	242
	6.3.3 Disk Cooling Time Scale	243
	6.3.4 Infall-Driven Fragmentation	245
	6.3.5 Outcome of Disk Fragmentation	246
6.4	Further Reading	246
7	Early Evolution of Planetary Systems	247
7.1	Migration in Gaseous Disks	248
	7.1.1 Planet–Disk Torque in the Impulse Approximation	248
	7.1.2 Physics of Gas Disk Torques	251
	7.1.3 Torque Formulae	255
	7.1.4 Gas Disk Migration Regimes	257

<i>Contents</i>		ix
7.1.5	Gap Opening and Gap Depth	258
7.1.6	Coupled Planet–Disk Evolution	261
7.1.7	Eccentricity Evolution	264
7.2	Secular and Resonant Evolution	265
7.2.1	Physics of an Eccentric Mean-Motion Resonance	266
7.2.2	Example Definition of a Resonance	267
7.2.3	Resonant Capture	270
7.2.4	Kozai–Lidov Dynamics	272
7.2.5	Secular Dynamics	275
7.3	Migration in Planetesimal Disks	276
7.3.1	Application to Extrasolar Planetary Systems	280
7.4	Planetary System Stability	281
7.4.1	Hill Stability	282
7.4.2	Planet–Planet Scattering	287
7.4.3	The Titius–Bode Law	289
7.5	Solar System Migration Models	289
7.5.1	Early Theoretical Developments	290
7.5.2	The Nice Model	291
7.5.3	The Grand Tack Model	292
7.6	Debris Disks	293
7.6.1	Collisional Cascades	293
7.6.2	Debris Disk Evolution	298
7.6.3	White Dwarf Debris Disks	299
7.7	Further Reading	300
<i>Appendix A</i> Physical and Astronomical Constants		301
<i>Appendix B</i> The Two-Body Problem		302
<i>Appendix C</i> N-Body Methods		311
<i>References</i>		319
<i>Index</i>		329

Cambridge University Press
978-1-108-42050-1 — Astrophysics of Planet Formation
Philip J. Armitage
Frontmatter
[More Information](#)

Preface

The study of planet formation has a long history. The idea that the Solar System formed from a rotating disk of gas and dust – the *Nebula Hypothesis* – dates back to the writings of Kant, Laplace, and others in the eighteenth century. A quantitative description of terrestrial planet formation was already in place by the late 1960s, when Viktor Safronov published his now classic monograph *Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets*, while the main elements of the core accretion theory for gas giant planet formation were developed in the early 1980s. More recently, new observations have led to renewed interest in the problem. The most dramatic development has been the identification of extrasolar planets, first around a pulsar and subsequently in large numbers around main-sequence stars. These detections have allowed us to start to assess the Solar System’s place amid an extraordinary diversity of extrasolar planetary systems. The advent of high resolution imaging of protoplanetary disks and the discovery of the Solar System’s Kuiper Belt have been almost as influential, the former by providing direct information about the initial conditions for planet formation, the latter by highlighting the role of dynamics in the early evolution of planetary systems.

My goals in writing this text are to provide a concise introduction to the classical theory of planet formation and to more recent developments spurred by new observations. Inevitably, the range of topics covered is far from comprehensive. The emphasis is firmly on the *astrophysical* aspects of planet formation, including the physics of the protoplanetary disk, the agglomeration of dust into planetesimals and planets, and the dynamical interactions between those bodies and the disk and among themselves. The information that can be deduced from study of the chemical and geological makeup of Solar System bodies is discussed in places where that information is particularly pertinent, but this book is intended to complement rather than to replace textbooks on planetary science and cosmochemistry.

This book began as a graduate course that I taught at the University of Colorado in Boulder, for which the prerequisites were undergraduate classical physics and mathematical methods. The primary readership is beginning graduate students, but most of the text ought to be accessible to undergraduates who have had some

exposure to Newtonian mechanics and fluid dynamics. Although the mathematical demands are relatively elementary, the text does not shy away from covering modern theoretical developments, including those where research is very much still ongoing. Especially in these areas I provide extensive references to the technical literature to enable interested readers to explore further.

The decade since the first edition was published has seen further dramatic advances. NASA's *Kepler* mission has revolutionized our understanding of the population of relatively small extrasolar planets, while high resolution images of protoplanetary disks with *ALMA* have identified a wealth of largely unexpected structure. The chapter on observations has required major revision. On the theory side there has been intense interest in several processes that were either unknown or under-appreciated (at least by me) ten years ago, including pebble accretion, disk winds, the streaming instability, and vortices. Those omissions have been remedied. I have also added reference material on dynamics, and thoroughly revised the existing text to reflect both new thinking in areas such as planetary migration and my own teaching preferences.

My understanding of planet formation has been shaped by the many collaborators that I have had the privilege to work with. I am indebted to them, to the students in Boulder and at various summer schools who have informed my thinking about how best to teach the subject, and to the colleagues who have provided feedback and encouragement. Lastly, my thanks to Dada, whose unwavering support brought this new edition to fruition.